Modulation of Cosmic Ray Precipitation Related to Climate

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Short title: COSMIC RAY PRECIPITATION AND CLIMATE

Abstract.   High energy cosmic rays may influence the formation of clouds, and thus can have an impact on weather and climate. Cosmic rays in the solar wind are incident on the magnetosphere boundary and are then transmitted through the magnetosphere and atmosphere to reach the upper troposphere. The flux to the troposphere will depend both on the intensity and spectrum of the cosmic rays at the outer boundary of the magnetosphere (magnetopause) and on the configuration of the magnetosphere through which they propagate. Both the incident flux and the magnetospheric transmission have changed systematically during this century due to systematic changes in the solar wind. We show that, early in the century the region of the troposphere open to cosmic ray precipitation was usually confined to a relatively small high-latitude region. As the century progressed there was a systematic increase in the size of this region by over $7°$. We suggest that these changes contributed to climate change during the last 100 years.

Introduction

Cosmic rays may play a role in climate by influencing the formation of clouds. Surface temperature is highly sensitive to cloud cover [*Dickinson*, 1975]. It has been shown [*Pudovkin and Vereteneko*, 1995] that the cloud cover of the high latitude atmosphere ($> 60°$) is correlated with changes (Forbush decreases) in the flux of galactic cosmic rays with energies between 100 MeV and 10 GeV. During a solar cycle about 3% of the observed global cloud cover correlated with cosmic ray flux [*Svensmark and Friis-Christensen*, 1997]; although the cloud optical thickness varies out of phase with cloudiness [*Kuang et al.*, 1998]. A possible mechanism for the correlation between cosmic rays and clouds involves the effect of cosmic rays on the atmospheric electric current which influences a freezing of supercooled liquid droplets on cloud tops [*Tinsley*, 1996].

Cosmic rays in the solar wind are incident on the magnetosphere boundary and are then transmitted through the magnetosphere and atmosphere to reach the upper troposphere, particularly at high latitudes. The flux to the troposphere will depend both on the intensity and spectrum of the cosmic rays at the outer boundary of the magnetosphere (magnetopause) and on the configuration of the magnetosphere through which they propagate. Both the incident flux and the magnetospheric transmission have changed systematically during this century due to systematic changes in the solar wind.

The difference between latitude and longitude defined with relation to the Earth's pole of rotation (geographic) and the Earth's magnetic pole (geomagnetic) play an important role in the changes of cosmic ray flux described here. In this paper latitude and longitude are geographic unless explicitly stated otherwise.

Both galactic and solar cosmic rays affect the Earth. However, only the galactic cosmic rays can cause climate change. This is because solar cosmic rays are sporadic events. These events are well known for their effects on the ionosphere and on spacecraft systems. These deleterious effects are due to the large fluxes at energies greater than

10-30 MeV/nucl. The particle energy spectrum is very steep and the fluxes of particles with energy > 100 MeV/nucl is relatively small. The number of such events, but not their intensity, varies as the sunspot number [*Feynman and Garrett,* 1988]. The number of events per year with $E > 100$ MeV/nucl that significantly exceed the galactic cosmic ray background is less than 5 during high solar activity [*Feynman et. al.,* 1993]. Thus these events are too weak and sporadic to be involved in climate change.

In this paper we discuss the time evolution of cosmic ray penetration to the Earth atmosphere during this century. We find systematic changes and suggest that these are a contributing factor to the climate change during this century.

Cosmic ray variation in the solar wind at 1 AU

The galactic cosmic ray intensity is modulated by the solar wind. The magnetic field in the solar wind is carried out by the wind and the cosmic ray particles are swept out by this field [*Parker,* 1965; *Yamada et al.,* 1998]. The flux of galactic cosmic rays to the magnetopause peaks at 300 to 600 MeV and decreases sharply with energy above 1 GeV. The $E > 100$ MeV galactic cosmic ray proton flux to the magnetopause is larger by a factor of about 5 [*Smart and Shea,* 1985] at times of low solar activity as compared to the flux at high solar activity. The solar cycle modulation decreases with energy and vanishes for energies as high as 10 GeV.

The solar wind also drives geomagnetic activity and the coupling between the wind and the magnetosphere is strongly correlated to the component of the magnetic field in the solar wind that is anti-parallel to the Earth's magnetic field [*Hirshberg,* 1969] and to the velocity with which that field is brought to the magnetosphere (solar wind velocity), c.f. articles in *Kamide and Slavin,* [1986]. A good measure of the solar wind strength during this century is the *aa* index of geomagnetic activity (Figure 1) . The solar cycle variation of the solar wind, corresponding to the cycle variation in cosmic ray intensity, is evident. Between 1900 and 1970 there was an increase in *aa* at solar

minima [*Feynman and Crooker,* 1978]. In contrast, the sunspot number returned to the same low values at each minimum.

Cliver et., [1998] has compared the minimum *aa* values with the Earth's surface temperature record and found a correlation of 0.95 between the two data sets starting in 1885. The solar irradiance proxy developed from the *aa* minima continues to track the Earth's surface temperature until the present [*Cliver et al.* , 1998]. This is in marked contrast to reconstructions based on sunspot number [*Solanki and Fligger,* 1998] in which the irradiance and the temperature are not correlated after 1978.

In a study of ^{14}C *Stuiver and Quay* [1980] found that the cosmic ray flux at the magnetopause was anticorrelated with *aa*. The systematic increase in the *aa* minima in Fig. 1 then reflects an increase in solar wind strength and hence a decrease in cosmic ray flux at the magnetopause. Thus the cosmic ray flux to the magnetopause is lower now than it was at the beginning of the century than it is at present. Since the solar cycle change in geomagnetic activity is approximately the same size as the increase due to the trend at *aa* minima [*Feynman and Crooker,* 1978] the total change in flux to the magnetopause between a solar activity minimum at the beginning of the century and a solar activity maximum now is about twice the current solar cycle change, i.e. a factor of 10 at 100 MeV and no change at 10 GeV.

Transmission of cosmic rays to the troposphere

When a cosmic ray particle enters the magnetosphere its trajectory is highly influenced by the Earth's magnetic field and the configuration of the magnetosphere. The main field of the Earth changes relatively slowly with time, but geomagnetic activity, which reflects the configuration of the magnetosphere, changes on time scales of minutes to days.

The transmission of a high energy charged proton in the Earth's field depends on the energy of the particle and the direction from which it comes. A useful concept is the

cosmic ray cutoff, i.e. the lowest latitude that a proton of a given energy will penetrate if it is vertically incident on the Earth's field. Three regions of transmission can be distinguished. There is a low latitude region where the field has a dipole configuration which is insensitive to solar wind conditions. The trajectory of a particle incident on this region can be calculated in a straightforward manner but only protons of very high energy will be able to penetrate to the troposphere. Since the flux of such particles is very small, effectively few cosmic rays reach the troposphere in this region. There is also a high latitude region (the polar cap) in which the Earth's field lines are essentially open to the solar wind and particles of all rigidities can find their way to the atmosphere. Between these two regions is a third region in which the transmission is dependent on the rigidity of the particle and the direction of incidence at the magnetopause. The paths of these particles are very complex. The auroral oval marks the transition between the open polar cap and the closed dipolar inner magnetosphere. Changes in the position of the auroral oval will be reflected in changes in the positions at which galactic cosmic rays impinge on the troposphere. Such changes will influence cloud formation and through that mechanism, may be expected to change the weather and climate.

Changes due to Earth's main field

One possible cause of change of the position of the auroral oval is evolution of the Earth's main magnetic field. The geomagnetic pole position changes with respect to the geographic pole over time scales of the order of many years. In addition, the dipole intensity changes and the higher order anomalies change strength and drift. *Roederer*, [1974] calculated the position of the line that encircles a constant magnetic flux corresponding to a shell of field lines that trace the maximum auroral precipitation in 1960, i. e. the auroral oval in 1960. The contour is at an invariant geomagnetic latitude of 68°. He then used the measured magnetic fields from 1910 to calculate the position of the oval in geographic coordinates at that time. In the northern hemisphere

there was essentially no change except between about 20° E to 140° E, that is between the longitudes of say Warsaw (21°E) and Tokyo (139° E). At the longitude of Moscow (59°E) the change in the position of the auroral oval due to changes in the main field was about 2° latitude; from 75° in 1900 to 73° in 1960. These main magnetic field changes can have had an effect on weather systems forming in this region and propagating to lower latitudes in Siberia. In the southern hemisphere the region in which the auroral oval position changed was restricted from 80° E to about 150° E. Again the maximum difference in the oval position was about 2°.

The effect of these changes in the main field on the *aa* index of magnetic activity is small. The *aa* index was formed by averaging a northern index measured at Greenwich and a southern index at Melbourne (see [*Mayaud,* 1980] for a description of the small changes that were made as time passed.) The main field change did not influence the oval position at Greenwich, and changed the oval position at Melbourne by 1°.

Changes due to the configuration of the magnetosphere

More significant was the effect of geomagnetic activity on cosmic ray cutoff latitudes. The position of the boundary of the high latitude open magnetic field region can be estimated from the position of the auroral oval. As geomagnetic activity increases, the auroral oval expands equatorward and the high latitude region of the magnetosphere, that maps to the tail, increases in size. The position of the equatorial boundary of the oval is very strongly correlated (0.89) to the midlatitude geomagnetic Kp index [*Gussenhoven et al.* , 1983]. Cosmic rays can reach the troposphere at much lower latitudes when the geomagnetic activity is more intense. Thus, the long term systematic changes in aa shown in Figure 1 will cause a long-term systematic change in the position of the auroral oval and hence intensity of the precipitation of high energy cosmic rays to the troposphere.

To find the position of the equatorward auroral boundary from the *aa* index we

take the equation found by *Gussenhoven et al.*, [1981] for the electron precipitation boundary vs. Kp for a magnetic local time of 19-20, $\theta_o = 71.2 - 2.0Kp$, where θ_o is the boundary of the oval in geomagnetic co-ordinates. Because correlations between the midlatitude indices (Kp, ap, aa, am) are typically 0.98 we transform this into an expression between θ_o and aa using the relationships between the midlatitude range indices given by *Mayaud*, [1983] :

$$\theta_o = 77.5 - 9.1\log_{10}(aa). \tag{1}$$

In Figure 2 this Eq. is applied to the daily values of aa and the annual average position is calculated. At minimum activity at the beginning of the century the annual average position of the auroral oval was over 71° geomagnetic latitude, whereas recently the annual average position was 67° geomagnetic, a difference of 4°. The change is more clearly illustrated in Figure 3 which shows the percent of days/year with the equatorward boundary of the auroral oval greater than 70° geomagnetic and less than 63°. We note, for example, that on 2/3 of the days in 1904 the auroral oval was northward of 70° and it was never south of 63°. Recently, however, we have experienced years when the boundary of the oval was equatorward of 63° geomagnetic 1/3 of the time and was almost never poleward of 70°. This change occurred in a systematic way as the century progressed, thus producing a systematic change in the precipitation of cosmic rays. This can be expected to have caused a change in cloud cover, possibly through the electrofreezing mechanism [*Tinsley,* 1996], or affect a height of the troposphere (*R. Salawitch*, private communication).

In Figure 4 we compare the area of the polar cap poleward of the auroral oval, (characterizing the cosmic ray penetration to the Earth atmosphere,) with the variations in the Earth's global temperature. Both data sets have been filtered with a 10 year running average. Although there some differences, the similarity of trends is evident. Note that the earliest data points may be inaccurate in both data sets. A major

difference occurred between 1940 and 1950. The correlation between these time series is 0.83.

Conclusions

The precipitation of galactic cosmic rays to the troposphere has changed in systematic ways during the last 100 years, both due to a long term decrease in the flux incident on the magnetosphere and to changes in the transmission of the charged particles through the magnetosphere. The changes in flux are energy dependent. At $E > 100$MeV the difference between the proton flux incident on the magnetosphere at solar minimum and that incident at recent solar maxima is estimated to be a factor of 10, whereas at 10 GeV no change is expected. Changes in the Earth's main field caused a maximum change in the position of the auroral oval of about 2° confined to longitudes between 60°E and 140° E in both hemispheres. The largest effect on the cosmic ray precipitation was due to systematic changes in geomagnetic activity. The high latitude regions of the magnetosphere which are open to cosmic ray fluxes systematically increased over the last century. In recent years, the equatorward boundary of the auroral oval, which measure the size of the open region, was below 63° geomagnetic degrees on 1/4 of the days and rarely was northward of 70° geomagnetic. In contrast, at the beginning of the century there were years in which the boundary was north of 70° geomagnetic on more than half the days and almost never equatorward of 63°. We suggest that these systematic changes, complex as they are, modulated the distribution of clouds and hence contributed to climate change.

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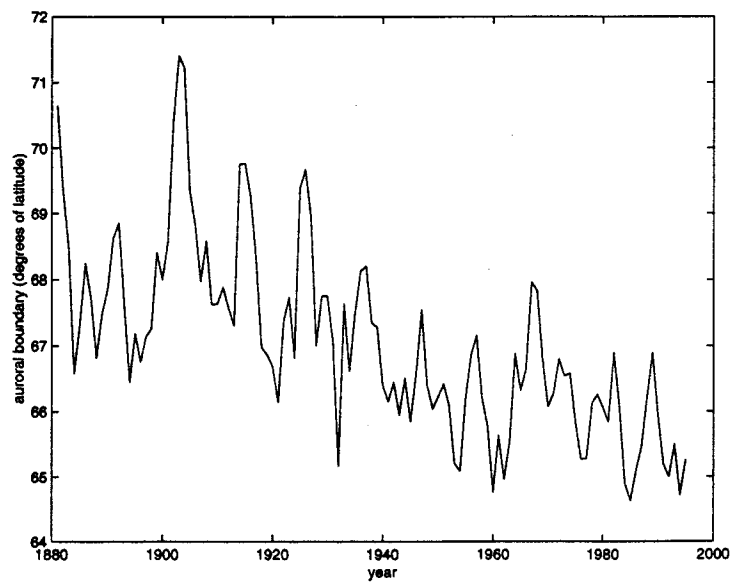

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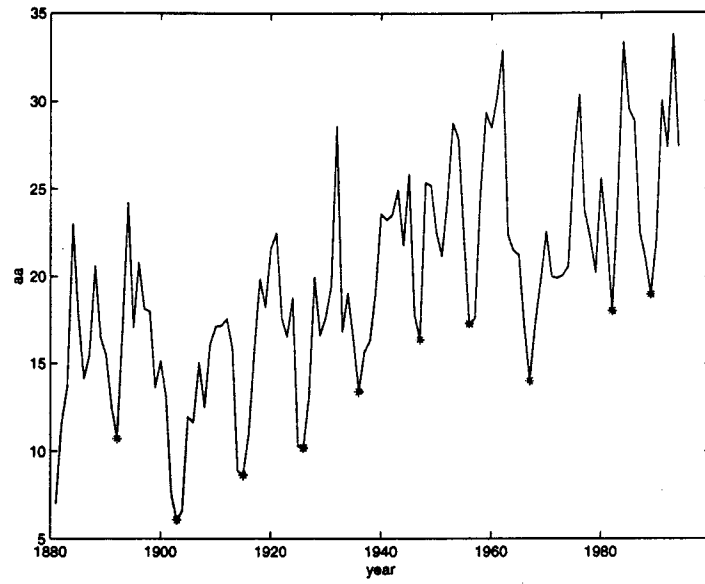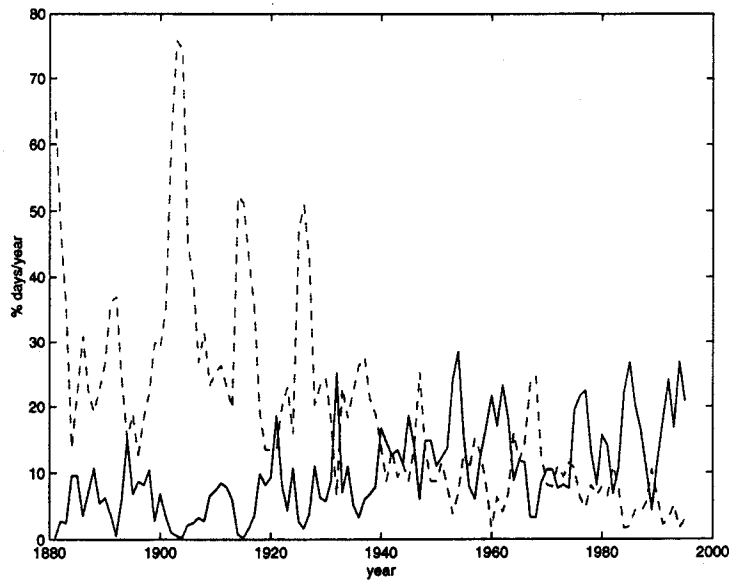
Figure 1. Annual average of *aa* index of the geomagnetic activity.

Figure 2. Annual average position (in geomagnetic coordinates) of the equatorward boundary of the auroral oval for about a 100 year period.

Figure 3. The percentage of days per year when the equatorward boundary of the auroral oval was greater than 70° geomagnetic (dashed line) and less than 63° geomagnetic (solid line).
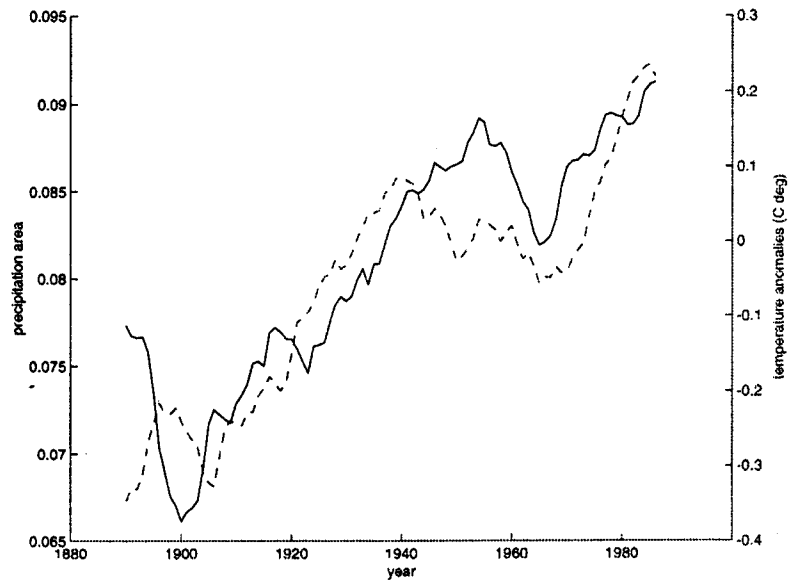
Figure 4. The 10 year running averages of the high-latitude area (in units of the Earth's hemisphere) open to energetic cosmic ray precipitation compared with the Earth's global temperature (data from [*Jones*, 1994]).